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14. ABSTRACT
We developed dynamic simulation models for portable, light-weight, high-energy-density power sources, especially those utilizing advanced electrochemical energy sources (e.g. polymer electrolyte membrane fuel cells) and energy storage elements (e.g. batteries, ultra-capacitors) and used those simulation models to study the performance of those power sources in specific applications such as electric vehicles or man-portable electronics. We developed component models and then used the VTB environment to assemble those components into complex systems. We produced models of photovoltaic solar cells, hydrogen-fueled polymer electrolyte membrane fuel cells, and electrochemical double-layer capacitors. We leveraged other work that developed models of lithium-ion batteries, and developed strong synergistic relationships between the departments of Electrical Engineering and Chemical Engineering. The work developed models of soldier system loads, both in the form of individual components such as radios and computers, and in the form of abstract electronic suites that have probabalistically-determined power demands.

15. SUBJECT TERMS
fuel cell, modeling, simulation, VTB, soldier system, electric vehicle, hybrid power source

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FINAL REPORT

MODELING OF POWER SYSTEMS FOR MARINES
Contract # N00014-00-1-0368

submitted to:
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20 NOVEMBER 2003

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Report Organization

This report is organized as follows: A short overview document describes at a high level the technical accomplishments of the program and summarizes the outcomes from support of graduate students. Then the main technical content follows in the form of reprint or draft publications that resulted from the work.

Summary of Technical Accomplisments

Our objective was to develop dynamic simulation models for portable, light-weight, high-energy-density power sources, especially those utilizing advanced electrochemical energy sources (e.g. polymer electrolyte membrane fuel cells) and energy storage elements (e.g. batteries, ultra-capacitors) and to use those simulation models to study the performance of those power sources in specific applications such as electric vehicles or man-portable electronics. Our approach was to develop independent component models that could be connected together in the Virtual Test Bed (VTB) environment to form complete systems. This effort produced models of hydrogen-fueled polymer electrolyte membrane fuel cells, photovoltaic solar cells,and electrochemical double-layer capacitors. It leveraged results of other work that simultaneously developed models of lithium-ion batteries. Group members built and relied on strong synergistic relationships between the departments of Electrical Engineering and Chemical Engineering in order to accomplish the project goals.

The work also developed models of Marine equipment in two forms. The first form was as independent models of individual equipment such as radios or computers, including the typical power demand (use) cycle. The second form was as abstract electronic suites that have probabalistically-determined power demands. Models of the first form could be connected together to define a particular equipment complement that would be carried by an individual soldier in order to test the suitability of the power source for specific missions. In the second form, all of the components of an electronic suite, and the statistical properties of the use cycles for that electronic suite, were defined in a single spreadsheet which then "programmed" the abstract load to draw appropriate power from the power source under test. This probabalistic abstract electronics suite allows one to test the suitability of a power source under statistically varying conditions.

Specific equipment configurations that were investigated include a fuel cell powered battery charging station, a fuel cell - battery hybrid power source, a hybrid electric vehicle (HMMWV), and power sources for the Land Warrior (or similar) soldier systems. The electric HMMWV system model was developed first in the Advanced Continuous Simulation Language (ACSL), and then later as a native system in VTB. Since a strong focus of our work related to defining optimized power sources, some part of this work also addressed issues of control of the power electronics that manage the power sharing between components of hybrid power sources.

Systems that were modeled, simulated, and studied included:

- Fuel cell powered battery charging station, including hardware design and modeling, control design and modeling, and hardware validation of the design and of the system model

- Controls for battery/fuel cell hybrid power sources
- Solar power sources, including new methods for maximum power point tracking
- Hybrid Electric Vehicle interactive driving model – both in ACSL and VTB forms

New models that were developed include:

- Improved models of fuel cells, lithium ion batteries, and power converters
- Models of Soldier System power loads
- Generic probabalistic power load model, programmable via Excel spreadsheet

Outcomes from Graduate Student Support

This funding principally supported the work of 4 Ph.D. students. Two of those four essentially completed all of their work under this program, another one who will finish very soon, and the fourth, who started participating in this project as an undergraduate student, is now midway through his Ph.D. program.

- Dr. Lijun Gao, graduated
- Dr. Zhenhua Jiang, graduated
- Mark Blackwelder, several months from completing Ph.D.
- Eric Vilar; midway through Ph.D. program

In addition to these four students, another 12 graduate students were supported at various times to accomplish selected pieces of work under this program.

Summary of Publications

The following publications cited support under this program.

Submitted to Journals (under review)

"Real-Time Strategy for Active Power Sharing in a Fuel Cell Powered Battery Charging Station", Z. Jiang and R. Dougal, submitted to IEEE Transactions on Energy Conversion, 08/03.

"Simulation of a Dynamically-Coupled Metal-Hydride Hydrogen Storage and Fuel Cell System", Z. Jiang, R. Dougal, S. Liu, S. Gadre, A. Ebner, J. Ritter, submitted to IEEE Transactions on Energy Conversion, 07/03.

"Real-Time Strategy for Active Power Sharing in a Fuel Cell Powered Battery Charging Station," Z. Jiang, and R. A. Dougal, submitted to *IEEE Transactions on Power Electronics*, 04/03.

"Control Strategies for Active Power Sharing in a Fuel Cell Powered Battery Charging Station", Z. Jiang and R. Dougal, submitted to IEEE Transactions on Industry Applications, 02/03.

"Power Controller Design for Maximum Power Tracking in Solar Installations," E. Solodovnik, S. Liu, R. A. Dougal, submitted to *IEEE Transactions on Power Eelctronics*.

"Power Enhancement of an Actively-Controlled Battery/Ultracapacitor Hybrid," L. Gao, R. A. Dougal and S. Liu, submitted to *IEEE Transactions on Power Electronics*.

Published in Journals

"Synergetic Control of Power Converters for Pulse Current Charging of Advanced Batteries from a Fuel Cell Power Source", Z. Jiang and R. Dougal, IEEE Transactions on Power Electronics (To appear, accepted 11/03).

"Design and Testing of a Fuel-Cell Powered Battery Charging Station", Z. Jiang and R. Dougal, Journal of Power Sources, Vol. 115, No. 2, pp 279 - 287, April 2003.

Conference Proceedings

"Strategy for Active Power Sharing in a Fuel-Cell-Powered Charging Station for Advanced Technology Batteries", Z. Jiang and R. Dougal, Proceedings of IEEE Power Electronics Specialists Conference, Acapulco, Mexico, Vol. 1, pp. 81-87, June 15-19, 2003.

"Application of Virtual Test Bed in Design and Testing of Hybrid Electric Vehicles," L. Gao, R. A. Dougal, S. Liu and D. J. Patterson, *The 5th All Electric Combat Vehicle Conference*, June 2-5, 2003, France.

"Hybrid Electrical Military Vehicles: Fuel Cell Performance and Simulation", Dougal R., L. Gao, P.R. Palmer, J. B. Lakeman, J.T. Doggrell, Advanced Vehicle Technologies conference, April 7-10, 2003, Brussels, Belgium.

"Control Design and Testing of A Novel Fuel-Cell-Powered Battery-Charging Station", Z. Jiang and R. Dougal, Proceedings of IEEE Applied Power Electronics Conference, Miami, FL, Vol. 2, pp. 1127-1133, Feb. 9-13, 2003.

"Virtual Test Bed for Electrochemical Power Sources", L. Gao, M Blackwelder, Z. Wu and R. A. Dougal, *203rd Meeting of The Electrochemical Society,* Oct 20-25, 2002, Salt Lake City, USA.